FINAL REPORT

THE MOUNTAIN SNOWPACK AS AN ENVIRONMENTAL INDICATOR

BY

ARLIN B. SUPER

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13. ABSTRACT

The purpose of the research program reported upon herein was to gain an improved understanding of the interrelationships existing between the seasonal mountain snowpack and climate and terrain. The field investigations were carried out in the mountains of southwestern Montana over four winter seasons. Most of the studies were conducted in the Bridger Mountain Range near Bozeman, Montana.

The investigation evolved into three main areas of emphasis:

(1) Snowpack accumulation as related to terrain and meteorological factors.
(2) Remote sensing of snow surface temperature by infrared radiometry.
(3) Study of some of the physical properties of the seasonal mountain snowpack through snowpit sampling.

The results of investigation into each area of emphasis has been reported upon in a separate technical report. This final report is composed of the abstract and summary and conclusions of each of the three technical reports.

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TABLE OF CONTENTS

INTRODUCTION

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SNOWPACK ACCUMULATION IN RELATION TO TERRAIN AND METEOROLOGICAL FACTORS IN SOUTHWESTERN MONTANA

by

John T. McPartland
Arlin B. Super
Val L. Mitchell

August 1971

ABSTRACT

The relationships between mountain snowpack accumulation and terrain and meteorological parameters were investigated in three separate mountain areas in southwestern Montana.

The parameters used (elevation, aspect, slope, geographic location, and degree of potential windiness) were determined for each sampling site in the three study areas. These were used as terrain/meteorological parameters in the data analysis. Snowpack variables measured were snow depth and water equivalent.

Statistical treatment of the data was performed through use of simple correlation and multiple linear regression analyses, and by principal component analysis. Snow depth was used as the snowpack variable throughout all analyses. However, a very high simple linear correlation consistently existed between the snow depth and water equivalent, and it is concluded that results of the statistical analyses apply equally to water equivalents.

In the Bangtail area of the Bridger Range, elevation was

generally the most important variable in explaining variance in snowpack depth. The potential windiness parameters used were usually second in importance in explaining the depth variance. Southwest winds are known to be predominant in the area, and exposure to the southwest quadrant was the most significant of all the potential wind variables. Aspect, slope, and location parameters were generally not effective in explaining the variance in snowpack depth.

Variation in snowpack depth at the Carrot Basin area of the Madison Range and the Cooke City area of the Beartooth Range were largely explained by the elevation parameter. Wind effects in both areas were unimportant.

SUMMARY AND CONCLUSIONS

The study presented was initiated to investigate the relationships between mountain snowpack accumulation and terrain and meteorological parameters.

Three separate mountain areas were chosen to determine if consistent relationships between snowpack variations and variables selected for analysis could be developed in areas which differed in location and general landscape features.

Field investigations were conducted over a three-year period at sites situated in the Bridger, Madison, and Beartooth Ranges of southwestern Montana. Each of the research areas was generally downwind of a major orographic barrier and offered a wide range of diverse terrain and meteorological conditions for study and

comparison. In general, sampling sites in the Bangtail area of the Bridger Range occupied the widest range of topographic conditions. While some sites were along ridge crests or valley floors, most occupied intermediate positions. Topography in the Carrot Basin area of the Madison Range also allowed a wide range of site locations to be selected. These were generally confined to the region which tapers from the foot of the mountain peaks to the main valley floor some 10 miles east. Sites in the Cooke City area of the Beartooth Range were generally restricted to deep valley bottoms due to logistic considerations. Tree cover and terrain features within each of the areas was quite diverse, and it was possible to select sampling sites which covered a broad range of conditions.

The parameters elevation, aspect, slope, geographic location, and degree of potential windiness were measured for each sampling point in the three study areas. These were utilized as terrain/ meteorological variables in the statistical treatment of the data. For the Bangtail and Cooke City areas, two measures of potential wind effects at the sampling sites were utilized. These were a subjective wind factor and an objective exposure rating. The subjective system was applied by making value judgements based on a series of definitions (after Brown and Peck, 1962) as to the degree to which a site would be afforded protection from wind effects. The objective system was developed from panoramic photographs centered at each sampling location and was a measure of the percentage of photograph area which was not blocked by tree cover or terrain features. The objective classification was divided into four

separate parameters which allowed the amount of exposure in any of the four major quadrants to be used as individual variables. Due to lack of available field time, the objective exposure rating system was not applied to sites in the Carrot Basin Area of the Madison Range.

Snowpack variables measured were snow depth and water equivalent. During the first field season, core samples to determine the water content of the snowpack were only taken at selected sites in individual study areas. During the later phases of the field investigation, core samples were obtained at all sampling sites. Thus, there was substantially more information available for analysis on snow depth than on water equivalent. However, a very high linear correlation consistently existed between the snow depth and water equivalent values. From this, it was concluded that results of the statistical analyses using snow depth as the dependent variable would also be applicable to water equivalent information.

Statistical treatment of the data was performed through use of simple correlation and multiple linear regression analyses, and by principal component analysis. Snow depth was used as the snowpack variable throughout all analyses.

Simple linear correlation coefficients were first computed between snow depth and the terrain/meteorological variables. As a general rule, any variable which was not significantly correlated (5% level) with snow depth was excluded from further consideration.

The remaining variables were subjected to linear multiple correlation analysis, and the results were interpreted in terms of

the percent of the variance explained as expressed by the coefficient of multiple determination. This type of analysis has several restrictions which hinder interpretation of the results. Based on considerations of these restrictions, if an additional variable added to a grouping did not generally increase the total variance explained by at least 10%, the variable was not considered important. However, because variables must be assumed to be independent in this type of analysis, the order in which variables are added to a grouping can affect their apparent importance. Thus, physical reasoning also entered into the judgement of each variable's significance.

Principal component analysis avoids some of the restrictions imposed by the multiple linear regression technique, as the variables are grouped into independent combinations (eigenvectors) which describe the relationships which occur in the data. The first eigenvector produced explains the largest amount of variance and successive eigenvectors explained progressively less. All variables were initially considered in the principle component analysis, but only those that were most effective in explaining the variance were retained for final presentation. Due to the small number of variables finally utilized, strong interpretation is limited to the results shown by the first eigenvector.

Analysis of the data from the Bangtail area of the Bridger Range indicates that the following conclusions can be drawn:

(1) Elevation was generally the most important variable in explaining the variance in snowpack depth, with snow depth consistently increasing with elevation. More than

one-half the total explained variance was accounted for by the elevation parameter in the larger data grouping (N = 92). As the spring melt season was reached, elevation became progressively more important. This was probably due to the reduced effectiveness of wind in redistributing snow, because of wet spring snows and the presence of sun crusts, and to the occurrence of some melting at lower elevation sites.

(2) The potential windiness parameters used were usually second in importance in explaining the variance of snowpack depth. Occasionally they were more important than elevation, especially in the smaller data grouping (N = 66) and in early winter.

(3) The objective exposure system used was more effective in explaining variance than the subjective wind factor. In the Bangtail area where southwesterly winds are known to dominate, the exposure to the southwest was the most significant of all the potential wind variables. The combination of exposure to the southwest and elevation consistently accounted for the greatest amount of variance explained.

(4) The objective average exposure in all quadrants was still a better measure of potential wind effects at a site than the subjective wind factor.

(5) Aspect, slope, and location parameters were generally not effective in explaining the variance in snowpack depth.

Consideration of data from the Carrot Basin area revealed that only elevation was important in explaining the snow depth variance in

that area. Wind effects in the area were unimportant, even though much of the terrain is open and exposed. The lack of wind redistribution of snow in this area is not well understood, but may be partially due to effective blocking of low level winds by upwind ridges.

As in the Carrot Basin area, only elevation was significant in reducing the snowpack depth variance in the Cooke City area. Lack of wind effects may be due to the location of the majority of sampling sites in sheltered valley floor positions. However, it is not known whether more exposed ridge crest sites would be subjected to wind redistribution as travel to such sites was not practical.

Correlation coefficients between snow depth and water equivalent values were very high, and snowpack water content could be accurately estimated from snow depths in all three study areas if index density values were available and exposed sites were avoided. Networks of aerial snow depth markers established in locations protected from wind redistribution could provide accurate, useful water content estimates in any of the three mountain ranges.

Comparisons between the individual study areas revealed that total snow amounts received were quite comparable at the 8000 ft MSL level. Differences in snow on the ground at 8000 ft MSL were less than the annual variations experienced by the areas. However, comparison of snow depth gradients from 7000 to 8000 ft MSL revealed a high degree of variability in both space and time.

INFRARED TEMPERATURE SENSING OF SNOW-COVERED TERRAIN

by

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August 1971

ABSTRACT

The feasibility of remotely monitoring snow surface temperatures was investigated with a Barnes IT-3 infrared thermometer. Much of the work concentrated on determining the vertical emissivity of dry snow in the atmospheric infrared window region between 8 and 14 microns.

The emissivity of various snow surface types was measured using an apparatus called an emissivity box. An average emissivity for freshly fallen snow was found to be 0.975. For snow surfaces crusted by the effects of wind or melt phenomenon the average emissivity was 0.985. The mean emissivity for all snow surface types examined was 0.978. These high emissivity values substantiate the hypothesis that snow possesses approximately blackbody characteristics in the 8 to 14 micron spectral interval.

An analysis of errors in radiometrically obtained snow surface temperatures revealed that the IT-3 is capable of accurately measuring the true surface temperature to within two degrees Celsius for the temperature range experienced. Inversions in snow covered mountain valleys were successfully mapped during airborne case studies. Tops

of inversions were located by measuring the snow surface temperature variation with elevation and noting the intersection of the inversion top with the mountain slope.

Remote radiometric temperature sensing of snow surfaces appears to offer a potentially useful tool for monitoring surface temperature gradients in arctic environments. Its application to meteorological investigations of surface temperature variation in otherwise inaccessible mountainous regions in winter may also prove valuable.

SUMMARY AND CONCLUSIONS

The primary goal of the investigation was to determine the feasibility of remotely monitoring snow surface temperatures using an airborne infrared radiometer. The basic problem in this feasibility study was determination of the emissivity range of dry snow in the 8 to 14 micron spectral bandwidth. All radiometric measurements were made with a Barnes IT-3 Model-A infrared radiometer.

Emissivity measurements were made for 185 snow samples of varying crystalline form in the temperature range -1 to -18C. The technique utilized to perform the measurements was that of Buettner and Kern (1965), with some modification as recommended by Dana (1969). An instrument called an emissivity box was used in this approach. The vertical emissivity of snow in the 8 to 14 micron interval was found to range from 0.966 to 0.989. Freshly fallen snow exhibited an average emissivity of 0.975. Crusted snow was found to possess a mean emissivity of 0.985. The slightly higher emissivity of crusted snow may

be related to the greater number of crystals per unit area and increased density. The average emissivity for all types of snow surfaces examined was 0.978. Thus, it is concluded that snow possesses approximately blackbody characteristics in the 8 to 14 micron region. Lower emissivities found in the literature appear to be incorrect.

Airborne snow surface temperature measurements were shown to be feasible and accurate to within about 2C when obtained within 1000 ft of the surface. This value includes the effect of reflected radiation from the sky, emissivity corrections, and atmospheric absorption between the target and sensor. Tops of inversions in snow-covered mountain valleys were successfully mapped during airborne case studies. This demonstrates the practical applications of radiometers for detecting air mass boundaries at their intersection with the surface. Airborne radiometric measurements of snow surface temperature were generally found to agree within 2.5C with air temperature measured in weather shelters nearby. The only exception in the limited number of case studies was an instance where a strong inversion caused by radiation cooling resulted in a maximum difference of 5.8C between the radiant snow surface temperature and shelter temperature.

Radiometric temperature sensing of snow surfaces offers a useful tool in investigations of surface temperature gradients in arctic and alpine environments. Coupling an airborne infrared thermometer with an aircraft-mounted air temperature sensor provides the added capability for monitoring the temperature distribution of a remote area in three dimensions.

Airborne radiometric temperature sensing of snow-covered terrain offers a method of obtaining real-time surface temperature data in remote arctic and mountainous regions to supplement and improve satellite surface temperature information. Ultimately, satellite monitoring on a routine basis might be preferred. However, satellite scanning of the surface temperature has the disadvantage of being limited to cloudless conditions. Airborne radiometry, on the other hand, is restricted only by flying conditions. Airborne radiometers also provide more detail on surface temperature distributions than is possible with satellite-mounted sensors.

PHYSICAL INVESTIGATIONS OF THE SEASONAL MOUNTAIN SNOWPACK: BRIDGER RANGE, MONTANA

by

Arlin B. Super
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Val L. Mitchell

September 1971

ABSTRACT

Information on several mountain snowpack parameters was obtained from a number of snowpits dug in the Bridger Mountains of southwestern Montana. The data were collected during three winters from a total of three separate sites. The parameters studied included depth, density, age, grain size, ram resistance, shear vane strength, temperature, and air permeability. Air temperature, precipitation, and in some cases, wind speed were also measured.

Statistical analyses were performed to determine how the snowpack parameters were related. Snow density was strongly related to the overburden pressure or load of the overlying snowpack and to the age of the snowpack. The relationship with age apparently resulted from the rate of loading being approximately a linear function of time. Ram resistance was strongly related to density and shear vane strength, with the relationships being in good agreement with work done in other locations. Air permeability correlated significantly with depth, age, grain size, and shear vane strength, but the individual relationships were relatively weak.

SUMMARY AND CONCLUSIONS

An investigation of some of the physical parameters of the seasonal mountain snowpack was carried out in the Bridger Range of southwestern Montana. The field portion of the study extended through three winters with data being collected from three separate areas. The study areas were all clearings in the forest and ranged from very protected to somewhat windy.

Most snowpack parameters were sampled by digging pits through the pack and making measurements in a vertical profile along a pit wall. A total of 54 snowpits were sampled during the three field seasons. Parameters sampled included density, temperature, air permeability, ram resistance, shear vane strength, grain size, crystal type, and age of selected strata. Continuous air temperature and precipitation data were also available, and average daily wind speeds were measured during the last field season.

Snowpack data were stratified into three categories: regular snow, depth hoar, and isothermal snow. Interrelations were statistically derived between snowpack parameters for each type of snow. Differences between study sites were also examined.

The density of regular snow was found to be strongly dependent upon the amount of overburden pressure or load. Because the rate of loading was approximately constant with time, strong density-age relationships were apparent at individual study sites.

Even though the snow depth-density relationship varied from site to site and season to season, the relationship was strong.

The variations are probably related to windiness during and shortly after snowfall, to the rate of loading, and to the vertical temperature gradient through the snowpack. Depth hoar and isothermal snow displayed weak depth-density relationships.

Ram resistance was found to be highly related to snow density for both regular snow and depth hoar. The relationship for regular snow was in good agreement with some previous work. Ram resistance was also highly related to snow strength as measured by a torque shear vane for both depth hoar and regular snow. The relationship for regular snow was similar to those developed at Alta, Utah, and Goose Lake, Montana. This suggests that a single relationship exists for regular snow in the Northern Rockies.

Air permeability was found to be significantly correlated with depth, age, grain size, and shear strength but not with density. All significant correlation coefficients were negative with the exception of the coefficient relating permeability and grain size. The variance of permeability explained by any of the parameters measured was rather small.

LIST OF TECHNICAL REPORTS

Prepared For:
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McPartland, J. T., A. B. Super and V. L. Mitchell, August 1971, Snowpack accumulation in relation to terrain and meteorological factors in southwestern Montana. 96 pp.

Shafer, B. A. and A. B. Super, August 1971, Infrared temperature sensing of snow-covered terrain. 95 pp.

Super, A. B., J. T. McPartland and V. L. Mitchell, September 1971, Physical investigations of the seasonal mountain snowpack: Bridger Range, Montana. 50 pp.

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